5.1 Density

EXPLAIN THIS Does squeezing a loaf of bread increase its mass, its density, or both?

An important property of a material, whether in the solid, liquid, or gaseous phase, is the measure of compactness: **density.** We think of density as the "lightness" or "heaviness" of materials of the same size. It is a measure of how much mass occupies a given space; it is the amount of matter per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

FIGURE 5.1
When the volume of the bread is reduced, its density increases.

The densities of some materials are listed in Table 5.1. Mass is measured in grams or kilograms, and volume in cubic centimeters (cm^3) or cubic meters (m^3).* A gram of any material has the same mass as 1 cm^3 of water at a temperature of 4°C. So water has a density of 1 g/cm^3. Mercury's density is 13.6 g/cm^3, which means that it has 13.6 times as much mass as an equal volume of water. Iridium, a hard, brittle, silvery-white metal in the platinum family, is the densest substance on Earth.

A quantity known as weight density, commonly used when discussing liquid pressure, is expressed by the amount of weight per unit volume:**

$$\text{Weight density} = \frac{\text{weight}}{\text{volume}}$$

TABLE 5.1 DENSITIES

Material	(kg/m^3)
Solids	
Iridium	22,650
Osmium	22,610
Platinum	21,090
Gold	19,300
Uranium	19,050
Lead	11,340
Silver	10,490
Copper	8,920
Iron	7,870
Aluminum	2,700
Ice	919
Liquids	
Mercury	13,600
Glycerin	1,260
Seawater	1,025
Water at 4°C	1,000
Ethyl alcohol	785
Gasoline	680
Gases (kg/m^3 at sea level)	
Dry air:	
at 0°C	1.29
at 10°C	1.25
at 20°C	1.21
Helium	0.178
Hydrogen	0.090
Oxygen	1.43

CHECKPOINT

1. **Which has the greater density—1 kg of water or 10 kg of water?**
2. **Which has the greater density—5 kg of lead or 10 kg of aluminum?**
3. **Which has the greater density—an entire candy bar or half a bar?**

Were these your answers?

1. The density of any amount of water is the same: 1 g/cm^3 or, equivalently, 1000 kg/m^3, which means that the mass of water that would exactly fill a thimble of volume 1 cm^3 would be 1 g; or the mass of water that would fill a 1-m^3 tank would be 1000 kg. One kilogram of water would fill a tank only a thousandth as large, 1 L, whereas 10 kg would fill a 10-liter tank. Nevertheless, the important concept is that the ratio of mass/volume is the same for *any* amount of water.
2. Density is a *ratio* of weight or mass per volume, and this ratio is greater for any amount of lead than for any amount of aluminum—see Table 5.1.
3. Both the half and the entire candy bar have the same density.

fyi

- The metals lithium, sodium, and potassium (not in Table 5.1) are all less dense than water and float in water.

* A cubic meter is a sizable volume and contains a million cubic centimeters, so there are a million grams of water in a cubic meter (or, equivalently, a thousand kilograms of water in a cubic meter). Hence, 1 g/cm^3 = 1000 kg/m^3.

** Weight density is common to the United States Customary System (USCS) units, in which 1 ft^3 of fresh water (nearly 7.5 gallons) weighs 62.4 lb. So fresh water has a weight density of 62.4 lb/ft^3. Salt water is slightly denser at 64 lb/ft^3.

5.3 Buoyancy in a Liquid

EXPLAIN THIS Why is it easier to lift a boulder in water than out of water?

SCREENCAST: Buoyancy

VIDEO: Buoyancy

Anyone who has ever lifted a submerged object out of water is familiar with buoyancy, the apparent loss of weight of submerged objects. For example, lifting a large boulder off the bottom of a riverbed is a relatively easy task as long as the boulder is below the surface. When it is lifted above the surface, however, the force required to lift it is considerably more. This is because when the boulder is submerged, the water exerts an upward force on it—opposite in direction to gravity. This upward force is called the **buoyant force** and is a consequence of greater pressure at greater depth. Figure 5.8 shows why the buoyant force acts upward. Pressure is exerted everywhere against the object in a direction perpendicular to its surface. The arrows represent the magnitude and direction of forces at different places. Forces that produce pressures against the sides due to equal depths cancel one another. Pressure is greatest against the bottom of the boulder simply because the bottom of the boulder is deeper. Because the upward forces against the bottom are greater than the downward forces against the top, the forces do not cancel, and there is a net force upward. This net force is the buoyant force.

Stick your foot in a swimming pool and your foot is immersed. Jump in and sink and immersion is total—you're submerged.

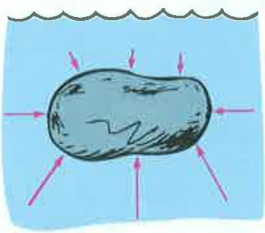


FIGURE 5.8
The greater pressure against the bottom of a submerged object produces an upward buoyant force.

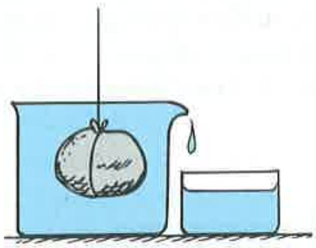


FIGURE 5.9
When a stone is submerged, it displaces a volume of water equal to the volume of the stone.

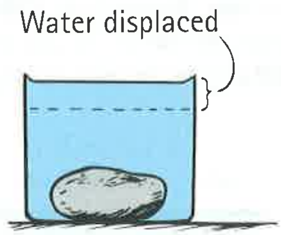


FIGURE 5.10
The raised level due to placing a stone in the container is the same as if a volume of water equal to the volume of the stone were poured in.

FIGURE 5.11
A liter of water occupies a volume of 1000 cm^3, has a mass of 1 kg, and weighs 9.8 N. Its density may therefore be expressed as 1 kg/L and its weight density as 9.8 N/L. (Seawater is slightly denser, 1.03 kg/L).

If the weight of the submerged object is greater than the buoyant force, the object sinks. If the weight is equal to the buoyant force acting upward on the submerged object, it remains at any level, like a fish. If the buoyant force is greater than the weight of the completely submerged object, it rises to the surface and floats.

Understanding buoyancy requires understanding the meaning of the expression "volume of water displaced." If a stone is placed in a container that is already up to its brim with water, some water overflows (Figure 5.9). Water is *displaced* by the stone. A little thought tells us that the *volume of the stone*—that is, the amount of space it occupies or its number of cubic centimeters—is equal to the *volume of water displaced.* Place any object in a container partially filled with water, and the level of the surface rises (Figure 5.10). How high? That would be to exactly the level that would be reached by pouring in a volume of water equal to the volume of the submerged object. This is a good method for determining the volume of irregularly shaped objects: *A completely submerged object always displaces a volume of liquid equal to its own volume.*

5.4 Archimedes' Principle

EXPLAIN THIS How can a concrete barge loaded with iron ore float?

The relationship between buoyancy and displaced liquid was first discovered in the third century BC by the Greek scientist Archimedes. It is stated as follows:

An immersed body is buoyed up by a force equal to the weight of the fluid it displaces.

This relationship is called **Archimedes' principle**. It applies to liquids and gases, which are both fluids. If an immersed body displaces 1 kg of fluid, the buoyant force acting on it is equal to the weight of 1 kg.* By *immersed,* we mean either *completely* or *partially submerged.* If we immerse a sealed 1-L container halfway into the water, it displaces half a liter of water and is buoyed up by the weight of half a liter of water. If we immerse it completely (submerge it), it is buoyed up by the weight of a full liter (or 1 kg) of water. Unless the completely submerged container is compressed, the buoyant force equals the weight of 1 kg at *any* depth. This is because, at any depth, it can displace no greater volume of water than its own volume. And the weight of this volume of water (not the weight of the submerged object!) is equal to the buoyant force.

If a 25-kg object displaces 20 kg of fluid upon immersion, its apparent weight equals the weight of 5 kg. Notice in Figure 5.12 that the 3-kg block has an apparent weight equal to the weight of 1 kg when submerged. The apparent weight of a submerged object is its weight out of water minus the buoyant force.

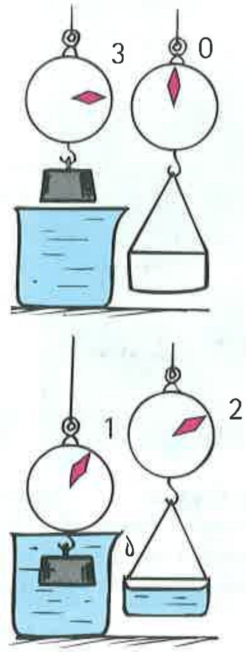


FIGURE 5.12
A 3-kg block weighs more in air than it does in water. When the block is submerged in water, its loss in weight is the buoyant force, which equals the weight of water displaced.

CHECKPOINT

1. **Does Archimedes' principle tell us that if an immersed block displaces 10 N of fluid, the buoyant force on the block is 10 N?**
2. **A 1-L container completely filled with lead has a mass of 11.3 kg and is submerged in water. What is the buoyant force acting on it?**
3. **A boulder is thrown into a deep lake. As it sinks deeper and deeper into the water, does the buoyant force on it increase? Decrease?**

Were these your answers?

1. Yes. Looking at it in a Newton's-third-law way, when the immersed block pushes 10 N of fluid aside, the fluid reacts by pushing back on the block with 10 N.
2. The buoyant force is equal to the weight of 1 kg (9.8 N) because the volume of water displaced is 1 L, which has a mass of 1 kg and a weight of 9.8 N. The 11.3 kg of the lead is irrelevant; 1 L of anything submerged in water displaces 1 L and is buoyed upward with a force 9.8 N, the weight of 1 kg. (Get this straight before going further!)
3. Buoyant force remains the same. It doesn't change as the boulder sinks because the boulder displaces the same volume of water at any depth. Because water is practically incompressible, its density is very nearly the same at all depths; hence, the weight of water displaced, or the buoyant force, is practically the same at all depths.

VIDEO: Archimedes' Principle

SCREENCAST: Buoyancy of a Submarine

SCREENCAST: More on Buoyancy

SCREENCAST: Buoyancy Problems

* A kilogram is not a unit of force but a unit of mass. So, strictly speaking, the buoyant force is not 1 kg, but the *weight* of 1 kg, which is 9.8 N. We could also say that the buoyant force is 1 *kilogram weight,* not simply 1 kg.

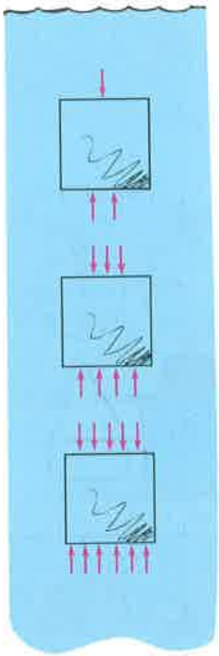


FIGURE 5.13
The difference between the upward and downward forces acting on the submerged block is the same at any depth.

Perhaps your instructor will summarize Archimedes' principle by way of a numerical example to show that the difference between the upward-acting and the downward-acting forces on a submerged cube (due to differences of pressure) is numerically identical to the weight of fluid displaced. It makes no difference how deep the cube is placed, because, although the pressures are greater with increasing depths, the *difference* between the pressure up against the bottom of the cube and the pressure exerted downward against the top of the cube is the same at any depth (Figure 5.13). Whatever the shape of the submerged body, the buoyant force is equal to the weight of fluid displaced.

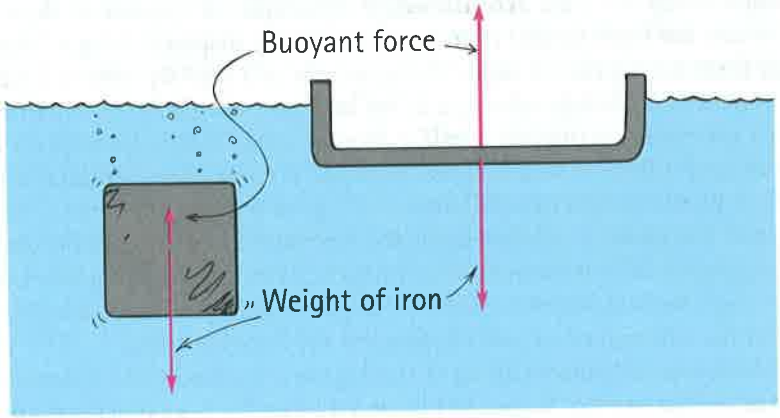


FIGURE 5.14
An iron block sinks, while the same quantity of iron shaped like a bowl floats.

Only in the special case of floating does the buoyant force acting on an object equal the object's weight.

VIDEO: Flotation

Flotation

Iron is much denser than water and therefore sinks, but an iron ship floats. Why is this so? Consider a solid 1-ton block of iron. Iron is nearly eight times as dense as water, so when it is submerged it displaces only $\frac{1}{8}$ ton of water, which is certainly not enough to prevent it from sinking. Suppose we reshape the same iron block into a bowl, as shown in Figure 5.14. It still weighs 1 ton. When we place it in the water, it settles into the water, displacing a greater volume of water than before. The deeper it is immersed, the more water it displaces and the greater the buoyant force acting on it. When the buoyant force equals 1 ton, the iron sinks no further.

When the iron boat displaces a weight of water equal to its own weight, it floats. This is called the **principle of flotation:**

A floating object displaces a weight of fluid equal to its own weight.

Every ship, submarine, or dirigible airship must be designed to displace a weight of fluid equal to its own weight. Thus, a 10,000-ton ship must be built wide enough to displace 10,000 tons of water before it immerses too deep in the water. The same applies to vessels in air. A dirigible or huge balloon that weighs 100 tons displaces at least 100 tons of air. If it displaces more, it rises; if it displaces less, it descends. If it displaces exactly its weight, it hovers at constant altitude.

FIGURE 5.15
The weight of a floating object equals the weight of the water displaced by the submerged part.

Because the buoyant force upon a body equals the weight of the fluid it displaces, denser fluids exert more buoyant force upon a body than less-dense fluids of the same volume. A ship therefore floats higher in salt water than in

PHYSICS IN HISTORY

Archimedes and the Gold Crown

According to legend, Archimedes (287–212 BC) had been given the task of determining whether a crown made for King Hiero II of Syracuse was of pure gold or contained some less expensive metals such as silver. Archimedes' problem was to determine the density of the crown without destroying it. He could weigh the crown, but determining its volume was a problem. The story tells us that Archimedes came to the solution when he noted the rise in water level while immersing his body in the public baths of Syracuse. Legend reports that he excitedly rushed naked through the streets shouting "Eureka! Eureka!" ("I have found it! I have found it!").

What Archimedes discovered was a simple and accurate way of finding the volume of an irregular object—the displacement method of determining volumes. Once he knew both the weight and volume, he could calculate the density. Then the density of the crown could be compared with the density of gold. Archimedes' insight preceded Newton's laws of motion, from which Archimedes' principle can be derived, by almost 2000 years.

Legend has it that the crown was not of pure gold.

fresh water because salt water is slightly denser than fresh water. In the same way, a solid chunk of iron floats in mercury even though it sinks in water.

The physics of Figure 5.16 is nicely employed by the Falkirk Wheel, a unique rotating boat lift that replaces a series of 11 locks in Scotland. A pair of water-filled tanks, called caissons, are connected on opposite sides of a 35-m-tall wheel. When a boat enters a caisson, the amount of water that overflows weighs exactly as much as the boat. As Figure 5.16 illustrates, each water-filled caisson weighs the same whether or not it carries boats (or multiple boats or even no boats as long as the water in each caisson has the same depth). The wheel always remains balanced as it rotates and lifts boats 18 m from a lower body of water to a higher one (Figure 5.17, next page). So, in spite of its enormous mass, the wheel rotates each half revolution with very little power input.

Notice in our discussion of liquids that Archimedes' principle and the law of flotation were stated in terms of *fluids,* not liquids. That's because although liquids and gases are different phases of matter, they are both fluids, with much the same mechanical principles. Let's turn our attention to the mechanics of gases in particular.

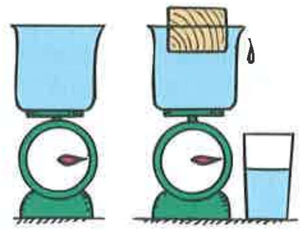


FIGURE 5.16
A floating object displaces a weight of fluid equal to its own weight.

fyi

- People who can't float are, 9 times out of 10, males. Most males are more muscular and slightly denser than females. Also, cans of diet soda float, whereas cans of regular soda sink in water. What does this tell you about their relative densities?

LINK TO EARTH SCIENCE

Floating Mountains

Mountains float on Earth's semiliquid mantle just as icebergs float in water. Both the mountains and icebergs are less dense than the material they float upon. Just as most of an iceberg is below the water surface (90%), most of a mountain (about 85%) extends into the dense semiliquid mantle. If you could shave off the top of an iceberg, the iceberg would be lighter and be buoyed up to nearly its original height before its top was shaved. Similarly, when mountains erode they are lighter, and are pushed up from below to float to nearly their original heights. So when a kilometer of mountain erodes away, some 85% of a kilometer of mountain returns. That's why it takes so long for mountains to weather away. Mountains, like icebergs, are bigger than they appear to be. The concept of floating mountains is *isostacy*—Archimedes' principle for rocks.

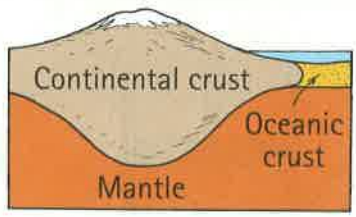
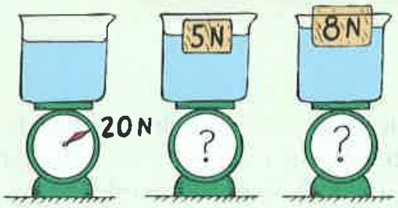



FIGURE 5.17
The Falkirk Wheel has two balanced, water-filled caissons, one moving up while the other moves down. The caissons rotate as the wheel turns so the water and boats don't tip out as the wheel makes each half revolution.

SCREENCAST: Archimedes

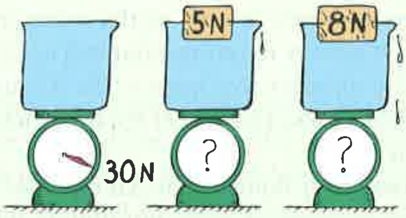
CHECKPOINT

1. **A beaker more than half full of water weighs 20 N. What will be the scale reading when**



   (a) 5-N block of wood floats in it?
   (b) an 8-N block of wood floats in it?

2. **When brimful of water, the same beaker weighs 30 N. What will be the scale reading, after overflow, when**



   (a) a 5-N block of wood floats in it?
   (b) an 8-N block of wood floats in it?

Were these your answers?

1. The scale readings will increase as weight is added: (a) 20 N + 5 N = 25 N, (b) 20 N + 8 N = 28 N.
2. For the brimful beaker, the displacement of water by the floating blocks causes water to overflow. (a) The 5-N block causes an overflow of 5 N of water, and (b) the 8-N block spills 8 N of water. So the scale reading doesn't change; it remains 30 N.

5.5 Pressure in a Gas

EXPLAIN THIS Why is holding your breath a no-no for scuba divers ascending to the surface of the water?

The primary difference between a gas and a liquid is the distance between molecules. In a gas, the molecules are far apart and free from the cohesive forces that dominate their motions in the liquid and solid phases.

Molecular motions in a gas are less restricted. A gas expands, fills all space available to it, and exerts a pressure against its container. Only when the quantity of gas is very large, such as in Earth's atmosphere or a star, do the gravitational forces limit the size or determine the shape of the mass of gas.

Liquids and gases are both fluids. A gas takes the shape of its container. A liquid does so only below its surface.

Boyle's Law

The air pressure inside the inflated tires of an automobile is considerably greater than the atmospheric pressure outside. The density of air inside is also greater than that of the air outside. To understand the relation between pressure and density, think of the molecules of air (primarily nitrogen and oxygen) inside the tire. The air molecules behave like tiny billiard balls, randomly moving and banging against the inner walls, producing a jittery force that appears to our coarse senses as a steady push. This pushing force, averaged over the wall area, provides the pressure of the enclosed air.

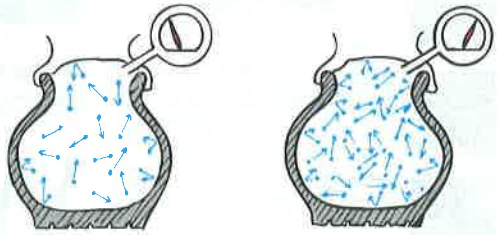


FIGURE 5.18
When the density of gas in the tire is increased, pressure is increased.

Suppose there are twice as many molecules in the same volume (Figure 5.18). Then the air density is doubled. If the molecules move at the same average speed—or, equivalently, if the gas has the same temperature—then the number of collisions is doubled. This means that the pressure is doubled. So pressure is proportional to density.

We double the density of air in the tire by doubling the amount of air. We can also double the density of a *fixed* amount of air by compressing it to half its volume. Consider the cylinder with the movable piston in Figure 5.19. If the piston is pushed downward so that the volume is half the original volume, the density of molecules is doubled, and the pressure is correspondingly doubled. Decrease the volume to a third of its original value, and the pressure is increased by a factor of 3, and so forth (provided the temperature remains the same).

SCREENCAST: Boyle's Law

Notice in these examples with the piston that the product of pressure and volume remains the same. For example, a doubled pressure multiplied by a halved volume gives the same value as a tripled pressure multiplied by a one-third volume. In general, we can state that the product of pressure and volume for a given mass of gas is a constant *as long as the temperature does not change. Pressure* × *volume* for a sample of gas at some initial time is equal to any *different pressure* × *different volume* of the same sample of gas at some later time. In shorthand notation,

$$P_1 V_1 = P_2 V_2$$

where P_1 and V_1 represent the original pressure and volume, respectively, and P_2 and V_2 the second pressure and volume. This relationship is called **Boyle's law,** after Robert Boyle, the 17th-century physicist who is credited with its discovery.*

Boyle's law applies to ideal gases. An ideal gas is one in which the disturbing effects of the forces between molecules and the finite size of the individual molecules can be neglected. Air and other gases under normal pressures and temperatures approach ideal gas conditions.

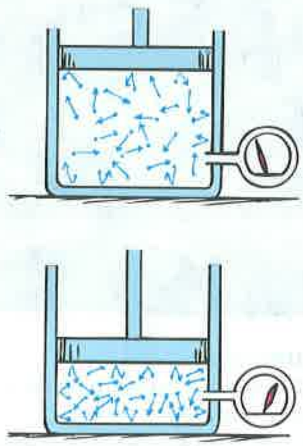


FIGURE 5.19
When the volume of gas is decreased, density and therefore pressure are increased.

CHECKPOINT

1. **A piston in an airtight pump is withdrawn so that the volume of the air chamber is tripled. What is the change in pressure?**
2. **A scuba diver breathes compressed air beneath the surface of water. If she holds her breath while returning to the surface, what happens to the volume of her lungs?**

* A general law that takes temperature changes into account is $P_1V_1/T_1 = P_2V_2/T_2$, where T_1 and T_2 represent the initial and final *absolute* temperatures, measured in SI units called kelvins (see Chapter 6).

Were these your answers?

1. The pressure in the piston chamber is reduced to one-third. This is the principle that underlies a mechanical vacuum pump.
2. When she rises toward the surface, the surrounding water pressure on her body decreases, allowing the volume of air in her lungs to increase—ouch! A first lesson in scuba diving is to not hold your breath when ascending. To do so can be fatal.

SCREENCAST: Atmospheric Pressure

VIDEO: Air Has Weight

VIDEO: Air Is Matter

VIDEO: Air Has Pressure

5.6 Atmospheric Pressure

EXPLAIN THIS How does the weight of air surrounding a planet affect atmospheric pressure at its surface?

We live at the bottom of an ocean of air. The atmosphere, much like the water in a lake, exerts a pressure. One of the most celebrated experiments demonstrating the pressure of the atmosphere was conducted in 1654 by Otto von Guericke, burgermeister of Magdeburg and inventor of the vacuum pump. Von Guericke placed together two copper hemispheres about 0.5 m in diameter to form a sphere, as shown in Figure 5.20. He set a gasket made of a ring of leather soaked in oil and wax between them to make an airtight joint. When he evacuated the sphere with his vacuum pump, two teams of eight horses each were unable to pull the hemispheres apart.

When the air pressure inside a cylinder like that shown in Figure 5.21 is reduced, an upward force is exerted on the piston. This force is large enough to lift a heavy weight. If the inside diameter of the cylinder is 12 cm or greater, a person can be lifted by this force.

What do the experiments of Figures 5.20 and 5.21 demonstrate? Do they show that air exerts pressure or that there is a "force of suction"? If we say there is a force of suction, then we assume that a vacuum can exert a force. But what is a vacuum? It is an absence of matter; it is a condition of nothingness. How can nothing exert a force? The hemispheres are not sucked together, nor is the piston holding the weight sucked upward. The pressure of the atmosphere is pushing against the hemispheres and the piston.

Interestingly, von Guericke's demonstration preceded knowledge of Newton's third law. The forces on the hemispheres would have been the same if he had used only one team of horses and tied the other end of the rope to a tree!

Just as water pressure is caused by the weight of water, **atmospheric pressure** is caused by the weight of air. We have adapted so completely to the invisible air that we sometimes forget it has weight. Perhaps a fish "forgets" about the weight of water in the same way. The reason we don't feel this weight crushing against our bodies is that the pressure inside our bodies equals that of the surrounding air. There is no net force for us to sense.

FIGURE 5.20
The famous "Magdeburg hemispheres" experiment of 1654, demonstrating atmospheric pressure. Two teams of horses couldn't pull the evacuated hemispheres apart. Were the hemispheres sucked together or pushed together? By what?

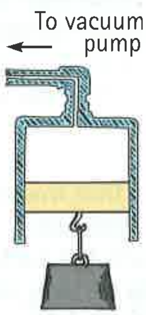


FIGURE 5.21
Is the yellow piston pulled upward by the vacuum in the chamber, or is it pushed upward by the atmosphere below it?

FIGURE 5.22
You don't notice the weight of a bag of water while you're submerged in water. Similarly, you don't notice that the air around you has weight.

At sea level, 1 m^3 of air at 20°C has a mass of about 1.2 kg. To estimate the mass of air in your room, estimate the number of cubic meters in the room, multiply by 1.2 kg/m^3, and you'll have the mass. Don't be surprised if it's heavier than your kid sister. If your kid sister doesn't believe air has weight, maybe it's because she's always surrounded by air. Hand her a plastic bag of water and she'll tell you it has weight. But hand her the same bag of water while she's submerged in a swimming pool, and she won't feel the weight. We don't notice that air has weight because we're submerged in air.

Whereas water in a lake has the same density at any level (assuming constant temperature), the density of air in the atmosphere decreases with altitude. Although 1 m^3 of air at sea level has a mass of about 1.2 kg, at 10 km, the same volume of air has a mass of about 0.4 kg. To compensate for this, airplanes are pressurized; the additional air needed to fully pressurize a 747 jumbo jet, for example, is more than 1000 kg. Air is heavy, if you have enough of it.

Consider the mass of air in an upright 30-km-tall hollow bamboo pole that has an inside cross-sectional area of 1 cm^2. If the density of air inside the pole matches the density of air outside, the enclosed mass of air would be about 1 kg. The weight of this much air is about 10 N. So the air pressure at the bottom of the bamboo pole would be about 10 N/cm^2. Of course, the same is true without the bamboo pole. There are 10,000 cm^2 in 1 m^2, so a column of air 1 m^2 in cross section that extends up through the atmosphere has a mass of about 10,000 kg. The weight of this air is about 100,000 N. This weight produces a pressure of 100,000 N/m^2—or equivalently, 100,000 pascals (Pa), or 100 kilopascals (kPa). To be more precise, the average atmospheric pressure at sea level is 101.3 kPa.*

The pressure of the atmosphere is not uniform. Besides altitude variations, there are variations in atmospheric pressure at any one locality due to moving fronts and storms. Measurement of changing air pressure is important to meteorologists in predicting weather.

FIGURE 5.23
The mass of air that would occupy a bamboo pole that extends to the "top" of the atmosphere is about 1 kg. This air has a weight of about 10 N.

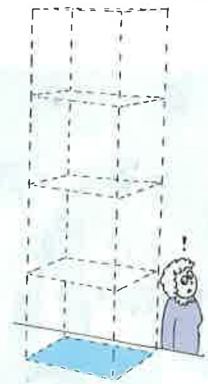


FIGURE 5.24
The weight of air that presses down on a 1-m^2 surface at sea level is about 100,000 N. So atmospheric pressure is about 10^5 N/m^2, or about 100 kPa.

CHECKPOINT

1. **Estimate the mass of air in kilograms in a classroom that has a 200-m^2 floor area and a 4-m-high ceiling. (Assume a chilly 10°C temperature.)**
2. **Why doesn't the pressure of the atmosphere break windows?**

Were these your answers?

1. The mass of air is 1000 kg. The volume of air is 200 m^2 × 4 m = 800 m^3; each cubic meter of air has a mass of about 1.25 kg, so 800 m^3 × 1.25 kg/m^3 = 1000 kg (about a ton).
2. Atmospheric pressure is exerted on *both* sides of a window, so no net force is exerted on the window. If for some reason the pressure is reduced or increased on one side only, as in a strong wind, then watch out!

Workers in underwater construction work in an environment of compressed air. The air pressure in their underwater chambers is at least as great as the combined pressure of water and atmosphere outside.

Barometers

An instrument used for measuring the pressure of the atmosphere is called a **barometer.** A simple mercury barometer is illustrated in Figure 5.25. A glass tube, longer than 76 cm and closed at one end, is filled with mercury and tipped

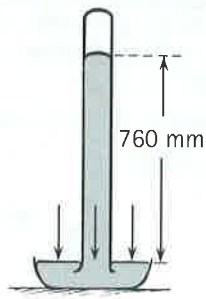


FIGURE 5.25
A simple mercury barometer. Mercury is pushed up into the tube by atmospheric pressure.

* The pascal is the SI unit of measurement. The average pressure at sea level (101.3 kPa) is often called 1 atmosphere (atm). In British units, the average atmospheric pressure at sea level is 14.7 lb/in^2 (pounds per square inch, or psi).

FIGURE 5.26
Strictly speaking, they do not suck the soda up the straws. They instead reduce pressure in the straws, which allows the weight of the atmosphere to press the liquid up into the straws. Could they drink a soda this way on the Moon?

FIGURE 5.27
The atmosphere pushes water from below up into a pipe that is evacuated of air by the pumping action.

When the pump handle is pushed down and the piston is raised, air in the pipe is "thinned" as it expands to fill a larger volume. Atmospheric pressure on the well surface pushes water up into the pipe, causing water to overflow at the spout.

upside down in a dish of mercury. The mercury in the tube flows out of the submerged open bottom until the difference in the mercury levels in the tube and the dish is 76 cm. The empty space trapped above, except for some mercury vapor, is a pure vacuum.

The explanation for the operation of such a barometer is similar to that of children balancing on a seesaw. The barometer "balances" when the weight of liquid in the tube exerts the same pressure as the atmosphere outside. Whatever the width of the tube, a 76-cm column of mercury weighs the same as the air that would fill a vertical 30-km tube of the same width. If the atmospheric pressure increases, then the atmosphere pushes down harder on the mercury in the dish and pushes the mercury higher in the tube. Then the increased height of the mercury column exerts an equal balancing pressure.

Water could instead be used to make a barometer, but the glass tube would have to be much longer—13.6 times as long, to be exact. The density of mercury is 13.6 times the density of water. That's why a tube of water 13.6 times longer than one of mercury (of the same cross section) is needed to provide the same weight as mercury in the tube. A water barometer would have to be 13.6×0.76 m, or 10.3 m high—too tall to be practical.

What happens in a barometer is similar to what happens when you drink through a straw. By sucking, you reduce the air pressure in the straw when it is placed in a drink. Atmospheric pressure on the drink then pushes the liquid up into the reduced-pressure region. Strictly speaking, the liquid is not sucked up; it is pushed up the straw by the pressure of the atmosphere. If the atmosphere is prevented from pushing on the surface of the drink, as in the party-trick bottle with the straw through an airtight cork stopper, one can suck and suck and get no drink.

If you understand these ideas, you can understand why there is a 10.3-m limit on the height to which water can be lifted with vacuum pumps. The old-fashioned farm-type pump shown in Figure 5.27 operates by producing a partial vacuum in a pipe that extends down into the water below. Atmospheric pressure on the surface of the water simply pushes the water up into the region of reduced pressure inside the pipe. Can you see that, even with a perfect vacuum, the maximum height to which water can be lifted in this way is 10.3 m?

A small portable instrument that measures atmospheric pressure is the *aneroid barometer* (Figure 5.28). A metal box partially exhausted of air with a slightly flexible lid bends in or out with changes in atmospheric pressure. Motion of the lid is indicated on a scale by a mechanical spring-and-lever system. Atmospheric pressure decreases with increasing altitude, so a barometer can be used to determine elevation. An aneroid barometer calibrated for altitude is called an *altimeter* (altitude meter). Some of these instruments are sensitive enough to indicate a change in elevation as you walk up a flight of stairs.*

Reduced air pressures are produced by pumps, which work by virtue of a gas tending to fill its container. If a space with less pressure is provided, gas flows from the region of higher pressure to the one of lower pressure. A vacuum pump simply provides a region of lower pressure into which the normally fast-moving gas molecules randomly move. The air pressure is repeatedly lowered by piston and valve action (Figure 5.29).

* Evidence of a noticeable pressure difference over a 1-m or less difference in elevation is any small helium-filled balloon that rises in air. The atmosphere really does push with more force against the lower bottom than against the higher top!

FIGURE 5.28
The aneroid barometer.

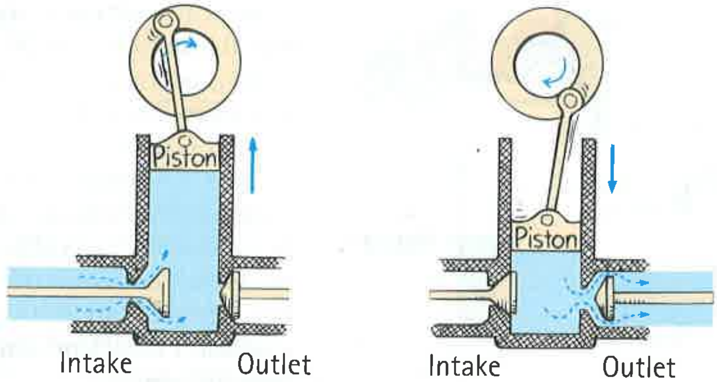


FIGURE 5.29
A mechanical vacuum pump. When the piston is lifted, the intake valve opens and air moves in to fill the empty space. When the piston is moved downward, the outlet valve opens and the air is pushed out. What changes would you make to convert this pump into an air compressor?

5.7 Pascal's Principle

EXPLAIN THIS How can small pressures in hydraulic machines produce large forces?

One of the most important facts about fluid pressure is that a change in pressure at one part of the fluid is transmitted undiminished to other parts. For example, if the pressure of city water is increased at the pumping station by 10 units of pressure, the pressure everywhere in the pipes of the connected system is increased by 10 units of pressure (providing the water is at rest). This rule is called **Pascal's principle:**

A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid.

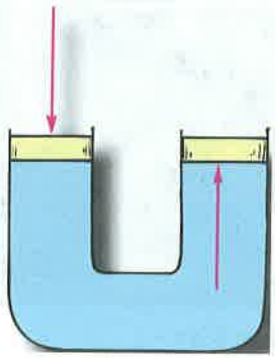


FIGURE 5.30
The force exerted on the left piston increases the pressure in the liquid and is transmitted to the right piston.

Pascal's principle was discovered in the 17th century by theologian and scientist Blaise Pascal, for whom the SI unit of pressure, the pascal (1 Pa $= 1\ N/m^2$), is named.

Fill a U-tube with water and place pistons at each end, as shown in Figure 5.30. Pressure exerted against the left piston is transmitted throughout the liquid and against the bottom of the right piston. (The pistons are simply "plugs" that can slide freely but snugly inside the tube.) The pressure that the left piston exerts against the water is exactly equal to the pressure the water exerts against the right piston. This is nothing to write home about. But suppose you make the tube on the right side wider and use a piston of larger area; then the result is impressive. In Figure 5.31 the piston on the right has 50 times the area of the piston on the left (say the left has 100 cm^2 and the right 5000 cm^2). Suppose a 10-kg load is placed on the left piston. Then an additional pressure due to the weight of the load is transmitted throughout the liquid and up against the larger piston. Here is where the difference between force and pressure comes in. The additional pressure is

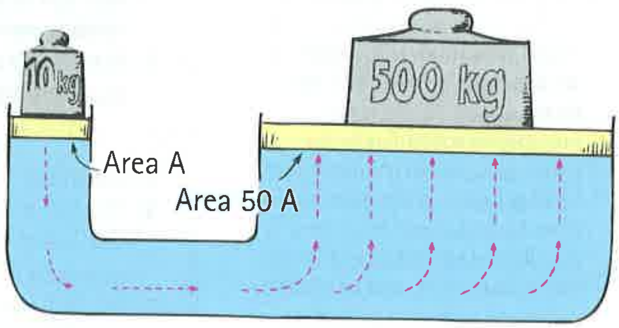


FIGURE 5.31
A 10-kg load on the left piston supports 500 kg on the right piston.

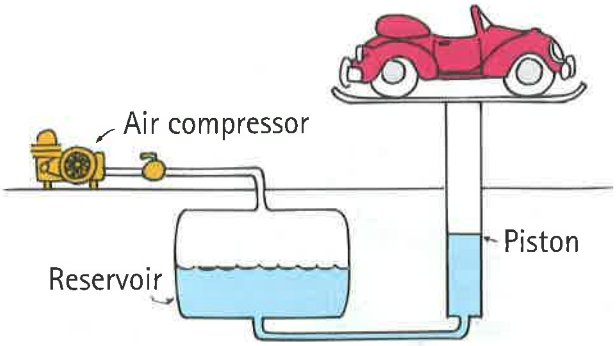


FIGURE 5.32
Pascal's principle in a service station.

SCREENCAST: Pascal's Principle

exerted against every square centimeter of the larger piston. Because there is 50 times the area, 50 times as much force is exerted on the larger piston. Thus, the larger piston supports a 500-kg load—50 times the load on the smaller piston!

This *is* something to write home about, for we can multiply forces using such a device. One newton of input produces 50 N of output. By further increasing the area of the larger piston (or reducing the area of the smaller piston), we can multiply force, in principle, by any amount. Pascal's principle underlies the operation of the hydraulic press.

The hydraulic press does not violate energy conservation, because a decrease in the distance moved compensates for the increase in force. When the small piston in Figure 5.31 is moved downward 10 cm, the large piston is raised only one-fiftieth of this, or 0.2 cm. The input force multiplied by the distance moved by the smaller piston is equal to the output force multiplied by the distance moved by the larger piston; this is one more example of a simple machine operating on the same principle as a mechanical lever.

Pascal's principle applies to all fluids, whether gases or liquids. A typical application of Pascal's principle for gases and liquids is the automobile lift seen in many service stations (Figure 5.32). Increased air pressure produced by an air compressor is transmitted through the air to the surface of oil in an underground reservoir. The oil in turn transmits the pressure to a piston, which lifts the automobile. The relatively low pressure that exerts the lifting force against the piston is about the same as the air pressure in automobile tires.

Hydraulics is employed by modern devices ranging from very small to enormous. Note the hydraulic pistons in almost all construction machines where heavy loads are involved (Figure 5.33).

FIGURE 5.33
Gears, pulleys, and cables have given way to hydraulic pistons in almost all of today's construction machines.

fyi

- Pascal was an invalid at age 18 and remained so until his death at age 39. He is remembered scientifically for hydraulics, which changed the technological landscape more than he imagined. He is remembered theologically for his many assertions, one of which relates to centuries of human landscape: "Men never do evil so cheerfully and completely as when they do so from religious conviction."

CHECKPOINT

1. **As the automobile in Figure 5.32 is being lifted, how does the change in oil level in the reservoir compare to the distance the automobile moves?**
2. **If a friend commented that a hydraulic device is a common way of multiplying energy, what would you say?**

Were these your answers?

1. The car moves up a greater distance than the oil level drops, because the area of the piston is smaller than the surface area of the oil in the reservoir.
2. No, no, no! Although a hydraulic device, like a mechanical lever, can multiply *force,* it always does so at the expense of distance. Energy is the product of force and distance. Increase one, decrease the other. *No device has ever been found that can multiply energy!*

5.8 Buoyancy in a Gas

EXPLAIN THIS How high will a helium-filled party balloon rise in air?

SCREENCAST: Buoyancy of Balloons

SCREENCAST: Air-Buoyancy Problem

A crab lives at the bottom of its ocean floor and looks upward at jellyfish and other lighter-than-water marine life drifting above it. Similarly, we live at the bottom of our ocean of air and look upward at balloons and other lighter-than-air objects drifting above us. A balloon is suspended in air and a jellyfish is suspended in water for the same reason: each is buoyed upward by a displaced weight of fluid equal to its own weight. Objects in water are buoyed upward because the pressure acting up against the bottom of the object exceeds the pressure acting down against the top. Likewise, air pressure acting upward against an object immersed in air is greater than the pressure above pushing down. The buoyancy in both cases is numerically equal to the weight of fluid displaced. Archimedes' principle applies to air just as it does for water:

An object surrounded by air is buoyed up by a force equal to the weight of the air displaced.

We know that a cubic meter of air at ordinary atmospheric pressure and room temperature has a mass of about 1.2 kg, so its weight is about 12 N. Therefore, any 1-m^3 object in air is buoyed up with a force of 12 N. If the mass of the 1-m^3 object is greater than 1.2 kg (so that its weight is greater than 12 N), it falls to the ground when released. If an object of this size has a mass of less than 1.2 kg, buoyant force is greater than weight and it rises in the air. Any object that has a mass that is less than the mass of an equal volume of air rises in the air. Stated another way, any object less dense than air rises in air. Gas-filled balloons that rise in air are less dense than air.

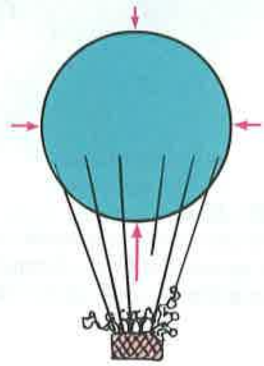


FIGURE 5.34
All bodies are buoyed up by a force equal to the weight of air they displace. Why, then, don't all objects float like this balloon?

No gas at all in a balloon would mean no weight (except for the weight of the balloon's material), but such a balloon would be crushed by atmospheric pressure. The gas used in balloons prevents the atmosphere from collapsing them. Hydrogen is the lightest gas, but it is seldom used because it is highly flammable. In sport balloons, the gas is simply heated air. In balloons intended to reach very high altitudes or to remain aloft for a long time, helium is commonly used. Its density is small enough that the combined weight of the helium, the balloon, and the cargo is less than the weight of air they displace. Low-density gas is used in a balloon for the same reason that cork is used in life preservers. The cork possesses no strange tendency to be drawn toward the water's surface, and the gas possesses no strange tendency to rise. Cork and gases are buoyed upward like anything else. They are simply light enough for the buoyancy to be significant.

VIDEO: Buoyancy of Air

Unlike water, the "top" of the atmosphere has no sharply defined surface. Furthermore, unlike water, the atmosphere becomes less dense with altitude. Whereas cork floats to the surface of water, a released helium-filled balloon does not rise to any atmospheric surface. Will a lighter-than-air balloon rise indefinitely? How high will a balloon rise? We can state the answer in several ways. A gas-filled balloon rises only so long as it displaces a weight of air greater than its own weight. Because air becomes less dense with altitude, a lesser weight of air is displaced per given volume as the balloon rises. When the weight of displaced air equals the total weight of the balloon, upward motion of the balloon ceases. We can also say that when the buoyant force on the balloon equals its weight, the balloon ceases rising. Equivalently, when the density of the balloon (including its load) equals the density of the surrounding air, the balloon ceases rising. Helium-filled toy rubber balloons usually break some time after being released into the air when the expansion of the helium they contain stretches the rubber until it ruptures.

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- If a balloon is free to expand when rising, it gets larger. But the density of surrounding air decreases. So, interestingly, the greater volume of displaced air doesn't weigh more, and buoyancy remains the same! If a balloon is not free to expand, buoyancy decreases as a balloon rises because of the less dense displaced air. Usually balloons expand when they initially rise, and if they don't eventually rupture, fabric stretching reaches a maximum and balloons settle where buoyancy matches weight.

CHECKPOINT

Is a buoyant force acting on you? If so, why are you not buoyed up by this force?

Was this your answer?

A buoyant force *is* acting on you, and you *are* buoyed upward by it. You aren't aware of it only because your weight is so much greater.

FIGURE 5.35
Because the flow is continuous, water speeds up when it flows through the narrow and/or shallow part of the brook.

Large helium-filled dirigible airships are designed so that when they are loaded, they slowly rise in air; that is, their total weight is a little less than the weight of air displaced. When in motion, the ship may be raised or lowered by means of horizontal "elevators."

Thus far we have treated pressure only as it applies to stationary fluids. Motion produces an additional influence.

5.9 Bernoulli's Principle

EXPLAIN THIS Why does a spinning baseball curve when thrown?

Consider a continuous flow of liquid or gas through a pipe: the volume of fluid that flows past any cross section of the pipe in a given time is the same as that flowing past any other section of the pipe—even if the pipe widens or narrows. For continuous flow, a fluid speeds up when it goes from a wide to a narrow part of the pipe. This is evident for a broad, slow-moving river that flows more swiftly as it enters a narrow gorge. It is also evident as water flowing from a garden hose speeds up when you squeeze the end of the hose to make the stream narrower.

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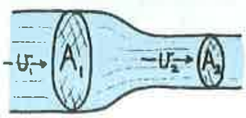
- Because the volume of water flowing through a pipe of different cross-sectional areas A remains constant, speed of flow v is high where the area is small and low where the area is large.



This is stated in the equation of continuity:

$$A_1v_1 = A_2v_2$$

The product A_1v_1 at point 1 equals the product A_2v_2 at point 2.

The motion of a fluid in steady flow follows imaginary *streamlines,* represented by thin lines in Figure 5.36 and in other figures that follow. Streamlines are the smooth paths of bits of fluid. The lines are closer together in narrower regions, where the flow speed is greater. (Streamlines are visible when smoke or other visible fluids are passed through evenly spaced openings, as in a wind tunnel.)

Daniel Bernoulli, an 18th-century Swiss scientist, studied fluid flow in pipes. His discovery, now called **Bernoulli's principle,** can be stated as follows:

Where the speed of a fluid increases, internal pressure in the fluid decreases.

Where streamlines of a fluid are closer together, flow speed is greater and pressure within the fluid is lower. Changes in internal pressure are evident for water containing air bubbles. The volume of an air bubble depends on the surrounding water pressure. Where water gains speed, pressure is lowered and bubbles become bigger. In water that slows, pressure is higher and bubbles are squeezed to a smaller size.

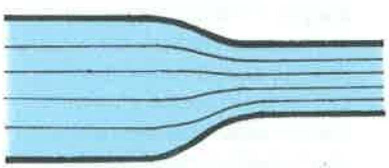


FIGURE 5.36
Water speeds up when it flows into the narrower pipe. The close-together streamlines indicate increased speed and decreased internal pressure.

Bernoulli's principle is a consequence of the conservation of energy, although, surprisingly, he developed it long before the concept of energy was formalized.*

* In mathematical form: $\frac{1}{2}mv^2 + mgy + pV =$ constant (along a streamline), where m is the mass of some small volume V, v its speed, g the acceleration due to gravity, y its elevation, and p its internal pressure. If mass m is expressed in terms of density ρ, where $\rho = m/V$, and each term is divided by V, Bernoulli's equation reads: $\frac{1}{2}\rho v^2 + \rho gy + p =$ constant. Then all three terms have units of pressure. If y does not change, an increase in v means a decrease in p, and vice versa. Note that when v is zero, Bernoulli's equation reduces to $\Delta p = \rho g \Delta y$ (weight density $\times$ depth).

The full energy picture for a fluid in motion is quite complicated. Simply stated, more speed and kinetic energy mean less pressure, and more pressure means less speed and kinetic energy.

Bernoulli's principle applies to a smooth, steady flow (called *laminar* flow) of constant-density fluid. At speeds above some critical point, however, the flow may become chaotic (called *turbulent* flow) and follow changing, curling paths called *eddies*. This exerts friction on the fluid and dissipates some of its energy. Then Bernoulli's equation doesn't apply well.

The decrease of fluid pressure with increasing speed may at first seem surprising, particularly if you fail to distinguish between the pressure *within* the fluid, internal pressure, and the pressure *by* the fluid on something that interferes with its flow. Internal pressure within flowing water and the external pressure it can exert on whatever it encounters are two different pressures. When the momentum of moving water or anything else is suddenly reduced, the impulse it exerts is relatively huge. A dramatic example is the use of high-speed jets of water to cut steel in modern machine shops. The water has very little internal pressure, but the pressure the stream exerts on the steel interrupting its flow is enormous.

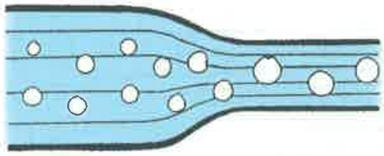


FIGURE 5.37
Internal pressure is greater in slower-moving water in the wide part of the pipe, as evidenced by the more-squeezed air bubbles. The bubbles are bigger in the narrow part because internal pressure there is less.

fyi

- The friction of both liquids and gases sliding over one another is called *viscosity* and is a property of all fluids.

Applications of Bernoulli's Principle

Anyone who has ridden in a convertible car with the canvas top up has noticed that the roof puffs upward as the car moves. This is Bernoulli's principle. The pressure outside—on top of the fabric, where air is moving—is less than the static atmospheric pressure on the inside.

Consider wind blowing across a peaked roof. The wind gains speed as it flows over the roof, as the crowding of streamlines in Figure 5.39 indicates. Pressure along the streamlines is reduced where they are closer together. The greater pressure inside the roof can lift it off the house. During a severe storm, the difference in outside and inside pressure doesn't need to be very much. A small pressure difference over a large area produces a force that can be formidable.

If we think of the blown-off roof as an airplane wing, we can better understand the lifting force that supports a heavy aircraft. In both cases, a greater pressure below pushes the roof or the wing into a region of lesser pressure above. Wings come in a variety of designs. What they all have in common is that air is made to flow faster over the wing's top surface than under its lower surface. This is mainly accomplished by a tilt in the wing, called its *angle of attack*. Then air flows faster over the top surface for much the same reason that air flows faster in a narrowed pipe or in any other constricted region. Most often, but not always, different speeds of airflow over and beneath a wing are enhanced by a

SCREENCAST: Bernoulli Principle

Recall from Chapter 3 that a large change in momentum is associated with a large impulse. So when water from a firefighter's hose hits you, the impulse can knock you off your feet. Interestingly, the pressure *within* that water is relatively small!

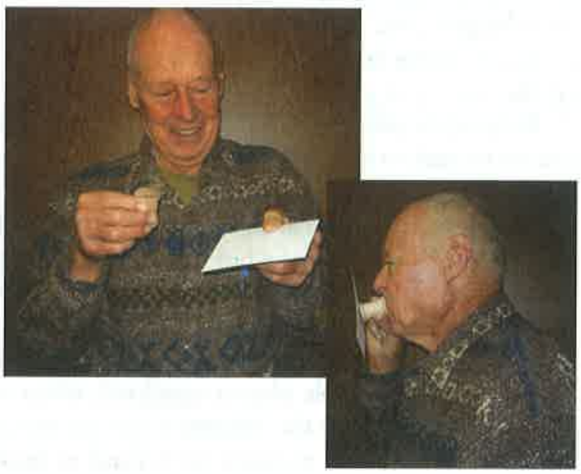


FIGURE 5.38
When Evan Jones blows through the hole in the spool and reduces air pressure between the card and the spool, the atmospheric pressure on the card's outside pushes it inward. (If you try this, punch a pin through the middle of the card for stability.)

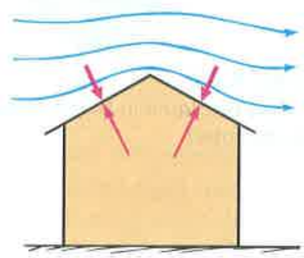


FIGURE 5.39
Air pressure above the roof is less than air pressure beneath the roof.

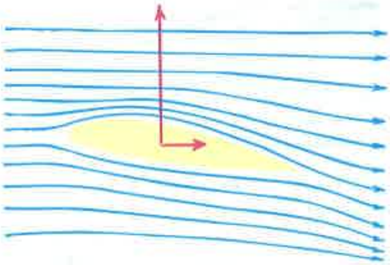


FIGURE 5.40
The vertical vector represents the net upward force (lift) that results from more air pressure below the wing than above the wing. The horizontal vector represents air drag.

SCREENCAST: Bernoulli Applications

difference in the curvature (*camber*) of the upper and lower surfaces of the wing. The result is more-crowded streamlines along the top wing surface than along the bottom. When the average pressure difference over the wing is multiplied by the surface area of the wing, we have a net upward force—lift. Lift is greater when there is a large wing area and when the plane is traveling fast. A glider has a very large wing area relative to its weight, so it does not have to be going very fast for sufficient lift. At the other extreme, a fighter plane designed for high-speed flight has a small wing area relative to its weight. Consequently, it must take off and land at high speeds.

We all know that a baseball pitcher can throw a ball in such a way that it curves to one side as it approaches home plate. This is accomplished by imparting a large spin to the ball. Similarly, a tennis player can hit a ball so it curves. A thin layer of air is dragged around the spinning ball by friction, which is enhanced by the baseball's threads or the tennis ball's fuzz. The moving layer of air produces a crowding of streamlines on one side. Note in Figure 5.41b that the streamlines are more crowded at B than at A for the direction of spin shown. Air pressure is greater at A, and the ball curves as shown.

Recent findings show that many insects increase lift by employing motions similar to those of a curving baseball. Interestingly, most insects do not flap their wings up and down. They flap them forward and backward, with a tilt that provides an angle of attack. Between flaps, their wings make semicircular motions to create lift.

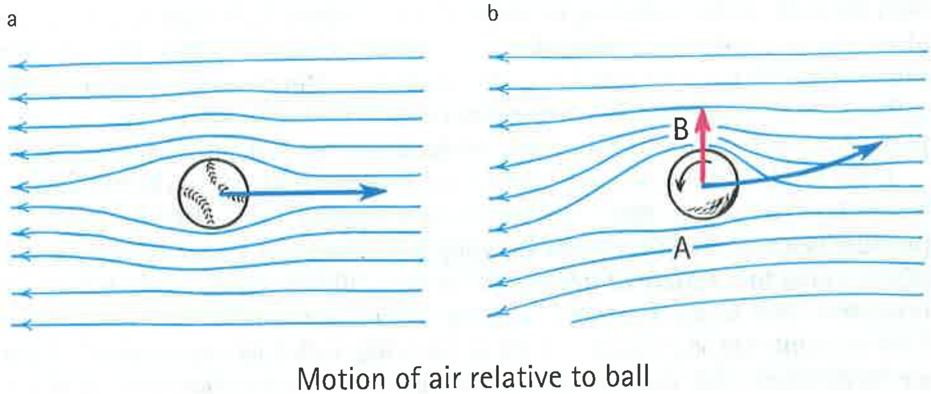


FIGURE 5.41
(a) The streamlines are the same on either side of a nonspinning baseball. (b) A spinning ball produces a crowding of streamlines. The resulting "lift" (red arrow) causes the ball to curve (blue arrow).

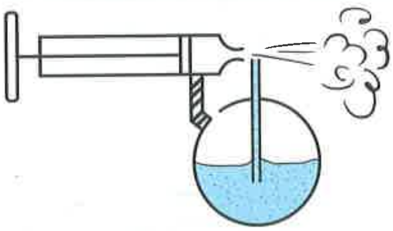


FIGURE 5.42
Why does the liquid in the reservoir go up the tube?

A familiar sprayer, such as a perfume atomizer, uses Bernoulli's principle. When you squeeze the bulb, air rushes across the open end of a tube inserted into the perfume. This reduces the pressure in the tube, whereupon atmospheric pressure on the liquid below pushes it up into the tube, where it is carried away by the stream of air.

Bernoulli's principle explains why trucks passing closely on the highway are drawn to each other, and why passing ships run the risk of a sideways collision. Water flowing between the ships travels faster than water flowing past the outer sides. Streamlines are closer together between the ships than outside, so water pressure acting against the hulls is reduced between the ships. Unless the ships are steered to compensate for this, the greater pressure against the outer sides of the ships forces them together. Figure 5.43 shows how to demonstrate this in your kitchen sink or bathtub.

Bernoulli's principle plays a small role when your bathroom shower curtain swings toward you in the shower when the water is on full blast. The pressure in the shower stall is reduced with fluid in motion, and the relatively greater

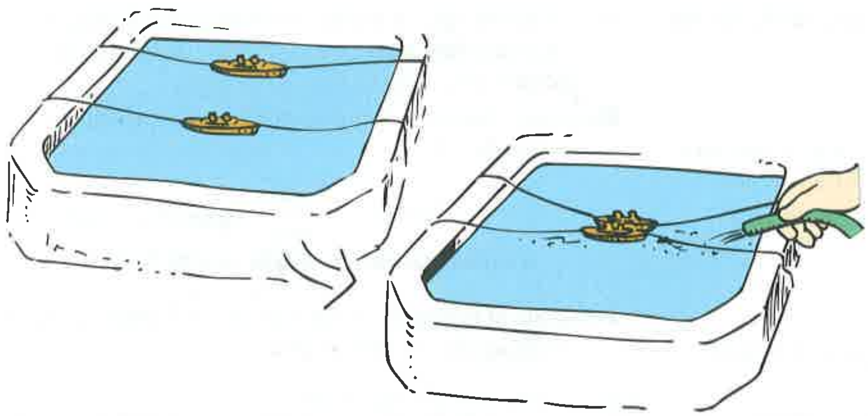
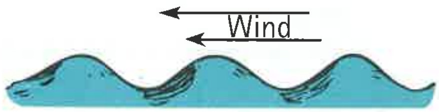


FIGURE 5.43
Try this in your sink. Loosely moor a pair of toy boats side by side. Then direct a stream of water between them. The boats draw together and collide. Why?

pressure outside the curtain pushes it inward. Like so much in the complex real world, this is just one of the physics principles that apply. More important is the convection of air in the shower. In any case, the next time you're taking a shower and the curtain swings in against your legs, think of Daniel Bernoulli.



CHECKPOINT

1. **On a windy day, waves in a lake or the ocean are higher than their average height. How does Bernoulli's principle contribute to the increased height?**
2. **Blimps, airplanes, and rockets operate under three very different principles. Which operates by way of buoyancy? Bernoulli's principle? Newton's third law?**
3. **Were birds able to fly before the time of Daniel Bernoulli?**

Were these your answers?

1. The troughs of the waves are partially shielded from the wind, so air travels faster over the crests. Pressure there is more reduced than down below in the troughs. The greater pressure in the troughs pushes water into the even higher crests.
2. Blimps operate by way of buoyancy, airplanes by Bernoulli's principle, and rockets by way of Newton's third law. Interesting, Newton's third law also plays a significant role in airplane flight—wing pushes air downward; air pushes wing upward.
3. No answer. (In a spirit of humor, discuss this with your friends.)

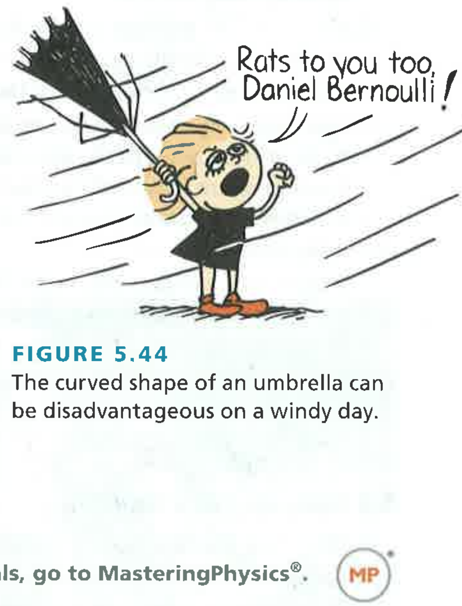


FIGURE 5.44
The curved shape of an umbrella can be disadvantageous on a windy day.

For assigned homework and other learning materials, go to MasteringPhysics®. MP

SUMMARY OF TERMS (KNOWLEDGE)

Archimedes' principle An immersed body is buoyed up by a force equal to the weight of the fluid it displaces (for both liquids and gases).

Atmospheric pressure The pressure exerted against bodies immersed in the atmosphere, resulting from the weight of air pressing down from above. At sea level, atmospheric pressure is about 101 kPa.

Barometer Any device that measures atmospheric pressure.

Bernoulli's principle The pressure in a fluid moving steadily, without friction or external energy input, decreases when the fluid velocity increases.

Boyle's law The product of pressure and volume is a constant for a given mass of confined gas regardless of changes in either pressure or volume individually, so long as temperature remains unchanged:

$$P_1V_1 = P_2V_2$$

Buoyant force The net upward force that a fluid exerts on an immersed object.

Density The amount of matter per unit volume:

$$\text{Density} = \frac{\text{mass}}{\text{volume}}$$

Weight density is expressed as weight per unit volume.

Pascal's principle A change in pressure at any point in an enclosed fluid at rest is transmitted undiminished to all points in the fluid.

Pressure The ratio of force to the area over which that force is distributed:

$$\text{Pressure} = \frac{\text{force}}{\text{area}}$$

$$\text{Liquid pressure} = \text{weight density} \times \text{depth}$$

Principle of flotation A floating object displaces a weight of fluid equal to its own weight.

READING CHECK QUESTIONS (UNDERSTANDING)

1. Give two examples of a fluid.

5.1 Density

2. What happens to the volume of a loaf of bread that is squeezed? What happens to the mass of the squeezed bread? What happens to the density of the squeezed bread?
3. Distinguish between mass density and weight density.

5.2 Pressure

4. Distinguish between force and pressure. Compare their units of measurement.
5. How does the pressure exerted by a liquid change with depth of the liquid? How does the pressure exerted by a liquid change as the density of the liquid changes?
6. Ignoring the pressure of the atmosphere, if you swim twice as deep beneath the water surface, how much more water pressure is exerted on your ears? If you swim in salt water, is the pressure greater than in fresh water at the same depth?
7. How does water pressure 1 m below the surface of a small pond compare to water pressure 1 m below the surface of a huge lake?
8. If you punch a hole in the side of a container filled with water, in what direction does the water initially flow outward from the container?

5.3 Buoyancy in a Liquid

9. Why does buoyant force act upward on an object submerged in water?
10. How does the volume of a completely submerged object compare with the volume of water displaced?

5.4 Archimedes' Principle

11. State Archimedes' principle.
12. What is the difference between being immersed and being submerged?
13. How does the buoyant force on a fully submerged object compare with the weight of water displaced?
14. What is the mass in kilograms of 1 L of water? What is its weight in newtons?
15. If a 1-L container is immersed halfway in water, what is the volume of water displaced? What is the buoyant force on the container?
16. Does the buoyant force on a floating object depend on the weight of the object or on the weight of the fluid displaced by the object? Or are these two weights the same for the special case of floating? Defend your answer.
17. What weight of water is displaced by a 100-ton floating ship? What is the buoyant force that acts on this ship?

5.5 Pressure in a Gas

18. By how much does the density of air increase when it is compressed to half its volume?
19. What happens to the air pressure inside a balloon when the balloon is squeezed to half its volume at constant temperature?

5.6 Atmospheric Pressure

20. What is the approximate mass in kilograms of a column of air that has a cross-sectional area of 1 cm^2 and extends from sea level to the upper atmosphere? What is the approximate weight in newtons of this amount of air?
21. How does the downward pressure of the 76-cm column of mercury in a barometer compare with the air pressure at the bottom of the atmosphere?
22. How does the weight of mercury in a barometer tube compare with the weight of an equal cross section of air from sea level to the top of the atmosphere?
23. Why would a water barometer have to be 13.6 times as tall as a mercury barometer?
24. When you drink liquid through a straw, is it more accurate to say that the liquid is pushed up the straw rather than sucked up? What exactly does the pushing? Defend your answer.

5.7 Pascal's Principle

25. What happens to the pressure in all parts of a confined fluid when the pressure in one part is increased?
26. Does Pascal's principle provide a way to get more energy from a machine than is put into it? Defend your answer.

5.8 Buoyancy in a Gas

27. A balloon that weighs 1 N is suspended in air, drifting neither up nor down. How much buoyant force acts upon it? What happens if the buoyant force decreases? If the buoyant force increases?

5.9 Bernoulli's Principle

28. What are streamlines? Is pressure greater or less in regions of crowded streamlines?

29. Does Bernoulli's principle refer to internal pressure changes in a fluid, to pressures that a fluid can exert on objects in the path of the flowing fluid, or to both?

30. What do peaked roofs, convertible tops, and airplane wings have in common when air moves faster across their top surfaces?

ACTIVITIES (HANDS-ON APPLICATION)

31. Try to float an egg in water. Then dissolve salt in the water until the egg floats. How does the density of an egg compare to that of tap water? To that of salt water?

32. Punch a couple of holes in the bottom of a water-filled container, and water spurts out because of water pressure. Now drop the container, and, as it freely falls, note that the water no longer spurts out. If your friends don't understand this, could you explain it to them?

33. Place a wet Ping-Pong ball in a can of water held high above your head. Then drop the can on a rigid floor. Because of surface tension, the ball is pulled beneath the surface as the can falls. What happens when the can comes to an abrupt stop is worth watching!

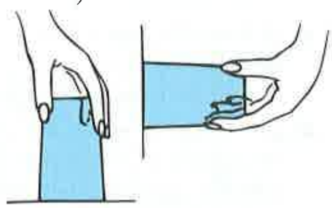
34. Try this in the bathtub or when you're washing dishes: Lower a drinking glass, mouth downward, over a small floating object such as a Ping-Pong ball. What do you observe? How deep must the glass be pushed in order to compress the enclosed air to half its volume? (You won't be able to do this in your bathtub unless it's 10.3 m deep!)

35. Compare the pressure exerted by the tires of your car on the road with the air pressure in the tires. For this project, you need to obtain your car's weight (from the Internet) and then divide by 4 to get the approximate weight supported by one tire. You can closely approximate the area of contact of a tire with the road by tracing the edges of tire contact on a sheet of paper marked with 1-inch squares beneath the tire. After you get the pressure of the tire on the road, compare it with the air pressure in the tire. Are they nearly equal? Which one is greater?

36. You ordinarily pour water from a full glass into an empty glass simply by placing the full glass above the empty glass and tipping. Have you ever poured air from one glass to another? The procedure is similar. Lower two glasses in water, mouths downward. Let one fill with water by tilting its mouth upward. Then hold the mouth of the water-filled glass downward above the air-filled glass. Slowly tilt the lower glass and let the air escape, filling the upper glass. You are pouring air from one glass into another!

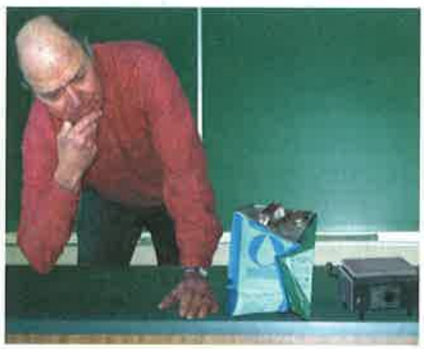
37. Raise a filled glass of water above the waterline, but with its mouth beneath the surface. Why does the water not flow out? How tall would a glass have to be before water began to flow out? (You won't be able to do this indoors unless you have a ceiling that is at least 10.3 m higher than the waterline.)

38. Place a card over the open top of a glass filled to the brim with water, and then invert it. Why does the card stay in place? Try it sideways.



39. Invert a water-filled soft-drink bottle or small-necked jar. Notice that the water doesn't simply fall out, but instead gurgles out of the container. Air pressure doesn't allow the water out until some air has pushed its way up inside the bottle to occupy the space above the liquid. How would an inverted, water-filled bottle pour out if you tried this on the Moon?

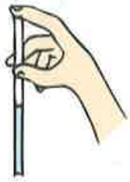
40. Do as Professor Dan Johnson does and pour about a quarter cup of water into a gallon or 5-liter metal can with a screw top. Place the can *open* on a stove, and heat it until the water boils and steam comes out of the opening. Quickly remove the can and screw the cap on tightly. Allow the can to stand. Steam inside condenses, which can be hastened by cooling the can with a dousing of cold water. What happens to the vapor pressure inside? (Don't do this with a can you expect to use again.)



41. Heat a small amount of water to boiling in an aluminum soft-drink can and invert it quickly into a dish of cold water. What happens is surprisingly dramatic!

42. Make a small hole near the bottom of an open tin can. Fill the can with water, which then proceeds to spurt from the hole. If you cover the top of the can firmly with the palm of your hand, the flow stops. Explain.

43. Lower a narrow glass tube or drinking straw into water and place your finger over the top of the tube. Lift the tube from the water and then lift your finger from the top of the tube. What happens? (You'll do this often in chemistry experiments.)



44. Push a pin through a small card and place it over the hole of a thread spool. Try to blow the card from the spool by blowing through the hole. Try it in all directions.

45. Hold a spoon in a stream of water as shown and feel the effect of the differences in pressure.

PLUG AND CHUG (FORMULA FAMILIARIZATION)

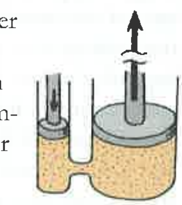
Pressure = weight density × depth

Neglect the pressure due to the atmosphere in the calculations that follow.

46. A 1-m-tall barrel is filled with water (with a weight density of 9800 N/m^3). Show that the water pressure on the bottom of the barrel is 9800 N/m^2, or, equivalently, 9.8 kPa.
47. Show that the water pressure at the bottom of the 50-m-high water tower in Figure 5.3 is 490,000 N/m^2, which is approximately 500 kPa.
48. The depth of water behind the Hoover Dam is 220 m. Show that the water pressure at the base of this dam is 2160 kPa.
49. The top floor of a building is 20 m above the basement. Show that the water pressure in the basement is nearly 200 kPa greater than the water pressure on the top floor.

THINK AND SOLVE (MATHEMATICAL APPLICATION)

50. Suppose that you balance a 2-kg ball on the tip of your finger, which has an area of 1 cm^2. Show that the pressure on your finger is 20 N/cm^2, which is 200 kPa.
51. A 12-kg piece of metal displaces 2 L of water when submerged. Show that its density is 6000 kg/m^3. How does this compare with the density of water?
52. A 1-m-tall barrel is closed on top except for a thin pipe extending 5 m up from the top. When the barrel is filled with water up to the base of the pipe (1 m deep) the water pressure on the bottom of the barrel is 9.8 kPa. What is the pressure on the bottom when water is added to fill the pipe to its top?
53. A rectangular barge, 5 m long and 2 m wide, floats in fresh water. Suppose that a 400-kg crate of auto parts is loaded onto the barge. Show that the barge floats 4 cm deeper.
54. Suppose that the barge in the preceding problem can be pushed only 15 cm deeper into the water before the water overflows to sink it. Show that it could carry three, but not four, 400-kg crates.
55. A merchant in Kathmandu sells you a 1-kg solid gold statue for a very reasonable price. When you arrive home, you wonder whether you got a bargain, so you lower the statue into a container of water and measure the volume of displaced water. Show that for 1 kg of pure gold, the volume of water displaced is 51.8 cm^3.
56. A vacationer floats lazily in the ocean with 90% of her body below the surface. The density of the ocean water is 1025 kg/m^3. Show that the vacationer's average density is 923 kg/m^3.
57. Your friend of mass 100 kg can just barely float in fresh water. Calculate her approximate volume.
58. In the hydraulic pistons shown, the smaller piston has a diameter of 2 cm. The larger piston has a diameter of 6 cm. How much more force can the larger piston exert compared with the force applied to the smaller piston?



59. On a perfect fall day, you are hovering at rest at low altitude in a hot-air balloon. The total weight of the balloon, including its load and the hot air in it, is 20,000 N. Show that the volume of the displaced air is about 1700 m^3.
60. What change in pressure occurs in a party balloon that is squeezed to one-third its volume with no change in temperature?

61. A mountain climber of mass 80 kg ponders the idea of attaching a helium-filled balloon to himself to effectively reduce his weight by 25% when he climbs. He wonders what the approximate size of such a balloon would be. Hearing of your legendary physics skills, he asks you. Share with him your calculations that show the volume of the balloon to be about 17 m^3 (slightly more than 3 m in diameter for a spherical balloon).

62. The weight of the atmosphere above 1 square meter of Earth's surface is about 100,000 N. Density, of course, becomes less with altitude. But suppose the density of air were a constant 1.2 kg/m^3. Calculate where the top of the atmosphere would be. How does this compare with the nearly 40-km-high upper part of the atmosphere?

63. The wings of a certain airplane have a total bottom surface area of 100 m^2. At a particular speed, the difference in air pressure below and above the wings is 4% of atmospheric pressure. Show that the lift on the airplane is 4×10^5 N.

THINK AND RANK (ANALYSIS)

64. Rank the following from most to least: (a) The pressure at the bottom of a 20-cm-tall container of salt water. (b) The pressure at the bottom of a 20-cm-tall container of fresh water. (c) The pressure at the bottom of a 5-cm-tall container of mercury.

65. Rank, from most to least, the percentage of volume above the water line for: (a) A basketball floating in fresh water. (b) A basketball floating in salt water. (c) A basketball floating in mercury.

66. Think about what happens to the volume of an air-filled balloon on top of water, and what happens to its volume beneath the water. Then rank, from most to least, the buoyant force on a weighted balloon in water when it is: (a) Barely floating with its top at the surface. (b) Pushed 1 m beneath the surface. (c) 2 m beneath the surface.

67. Rank, from greatest to least, the volumes of air in the glass when it is held: (a) Near the surface, as shown in the figure. (b) 1 m beneath the surface. (c) 2 m beneath the surface.

68. Rank, from greatest to least, the buoyant forces supplied by the atmosphere for: (a) An elephant. (b) A helium-filled party balloon. (c) A skydiver at terminal velocity.

69. Rank, from greatest to least, the amounts of lift on the following airplane wings. (a) Area 1000 m^2 with atmospheric pressure difference of 2.0 N/m^2. (b) Area 800 m^2 with atmospheric pressure difference of 2.4 N/m^2. (c) Area 600 m^2 with atmospheric pressure difference of 3.8 N/m^2.

EXERCISES (SYNTHESIS)

5.1 Density

70. When you squeeze a party balloon between your hands, what happens to the mass of the balloon? To its volume? To its density?

71. A can of diet soft drink floats in water, whereas a can of regular soft drink sinks. Discuss this phenomenon first in terms of density, then in terms of weight versus buoyant force.

72. The density of a rock doesn't change when it is submerged in water. Does your density change when you are submerged in water? Discuss and defend your answer.

5.2 Pressure

73. You know that a sharp knife cuts better than a dull knife. Do you know why this is so? Defend your answer.

74. Which is more likely to hurt—being stepped on by a 200-lb man wearing loafers or being stepped on by a 100-lb woman wearing high heels?

75. Stand on a bathroom scale and read your weight. When you lift one foot up so that you're standing on one foot, does the reading change? Does a scale read force or pressure?

76. Why are people who are confined to bed less likely to develop bedsores on their bodies if they use a waterbed rather than a standard mattress?

77. If water faucets upstairs and downstairs are turned fully on, does more water per second flow out the downstairs faucet? Or is the volume of water flowing from the faucets the same?

5.3 Buoyancy in a Liquid

78. What common liquid covers more than two-thirds of our planet, makes up 60% of our bodies, and sustains our lives and lifestyles in countless ways?

79. How much force is needed to push a nearly weightless but rigid 1-L carton beneath a surface of water?

80. Why is it inaccurate to say that heavy objects sink and that light objects float? Give exaggerated examples to support your answer.
81. Why does an inflated beach ball pushed beneath the surface of water swiftly shoot above the water surface when released?
82. A half-filled bucket of water is on a spring scale. Does the reading of the scale increase or remain the same when a fish is placed in the bucket? (Is your answer different if the bucket is initially filled to the brim?)
83. When a wooden block is placed in a beaker that is brim full of water, what happens to the scale reading after water has overflowed? Answer the same question for an iron block.

5.4 Archimedes' Principle

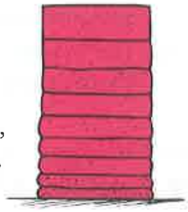
84. Why will a block of iron float in mercury but sink in water?
85. Why does a volleyball that is held beneath the surface of water have more buoyant force than a volleyball that is floating?
86. The mountains of the Himalayas are slightly less dense than the mantle material upon which they "float." Do you suppose that, like floating icebergs, they are deeper than they are high?
87. Give a reason why canal enthusiasts in Scotland appreciate the physics illustrated in Figure 5.16 (the block of wood floating in a vessel brim-filled with water).
88. The Falkirk Wheel in Scotland (Figure 5.17) rotates with the same low energy no matter what the weight of the boats it lifts. What would be different in its operation if, instead of carrying floating boats, it carried scrap metal that doesn't float?
89. One gondola in the Falkirk Wheel carries a 50-ton boat, while the opposite gondola carries a 100-ton boat. Why do the gondolas nevertheless weigh the same?
90. Both a 50-ton boat and a 100-ton boat float side by side in the gondola of the Falkirk Wheel, while the opposite gondola carries no boats at all. Why do the gondolas nevertheless weigh the same?
91. A ship sailing from the ocean into a fresh-water harbor sinks slightly deeper into the water. Does the buoyant force on it change? If so, does it increase or decrease?
92. In a sporting goods store, you see what appear to be two identical life preservers of the same size. One is filled with Styrofoam and the other one with lead pellets. If you submerge these life preservers in the water, upon which is the buoyant force greater? Upon which is the buoyant force ineffective? Why are your answers different?

5.5 Pressure in a Gas

93. Why is the pressure in an automobile's tires slightly greater after the car has been driven several kilometers?
94. How does the density of air in a deep mine compare with the air density at Earth's surface?
95. The "pump" in a vacuum cleaner is merely a high-speed fan. Would a vacuum cleaner pick up dust from a rug on the Moon? Explain.

5.6 Atmospheric Pressure

96. It is said that a gas fills all the space available to it. Why, then, doesn't the atmosphere go off into space?
97. Why is there no atmosphere on the Moon?
98. We can understand how pressure in water depends on depth by considering a stack of bricks. The pressure below the bottom brick is determined by the weight of the entire stack. Halfway up the stack, the pressure is half, because the weight of the bricks above is half. To explain atmospheric pressure, we should consider compressible bricks, like foam rubber. Why is this so?

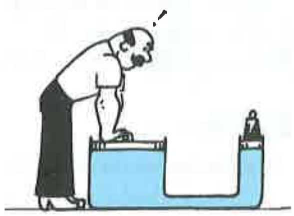


99. If you could somehow replace the mercury in a mercury barometer with a denser liquid, would the height of the liquid column be greater or less than with mercury? Why?
100. Would it be slightly more difficult to draw soda through a straw at sea level or on top of a very high mountain? Explain.
101. Richard's pump can operate at a certain maximum well depth in Pocatello, Idaho. Would this maximum depth be greater than, less than, or the same as if he pumps water in San Francisco?

102. Why is it so difficult to breathe when snorkeling at a depth of 1 m, and practically impossible at a depth of 2 m? Why can't a diver simply breathe through a hose that extends to the surface?

5.7 Pascal's Principle

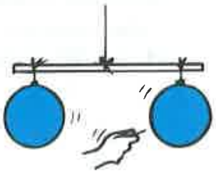
103. Say you've had a run of bad luck, and you slip quietly into a small, calm pool as hungry crocodiles lurking at the bottom are relying on Pascal's principle to help them to detect a tender morsel. What does Pascal's principle have to do with their delight at your arrival?
104. In the hydraulic arrangement shown, the larger piston has an area that is 50 times that of the smaller piston. The strong man hopes to exert enough force on the large piston to raise the 10-kg block that rests on the small piston. Do you think he will be successful? Defend your answer.



105. Why will the strong man in the previous exercise be more successful in lifting the 10-kg block if he switches places and pushes down on the smaller piston with the block on the larger piston?

5.8 Buoyancy in a Gas

106. Your friend says that the buoyant force of the atmosphere on an elephant is significantly greater than the buoyant force of the atmosphere on a small helium-filled balloon. What do you say?
107. When you replace helium in a balloon with hydrogen, which is less dense? Does the buoyant force on the balloon change if the balloon remains the same size? Explain.
108. A steel tank filled with helium gas doesn't rise in air, but a balloon containing the same gas easily does. Why?
109. Two identical balloons of the same volume are pumped up with air to more than atmospheric pressure and suspended on the ends of a stick that is horizontally balanced. One of the balloons is then punctured. Is there a change in the stick's balance? If so, which way does it tip?

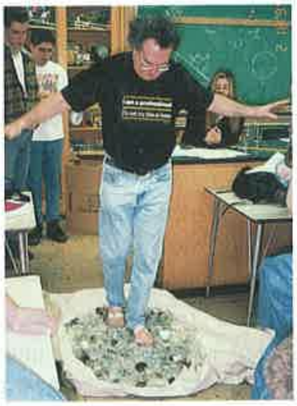


5.9 Bernoulli's Principle

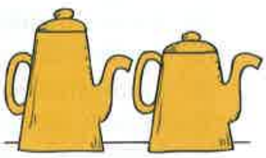
110. The force of the atmosphere at sea level against the outside of a 10-m^2 store window is about 1 million N. Why does this not shatter the window? Why might the window shatter in a strong wind blowing past the window?
111. How will two dangling vertical sheets of paper move when you blow between them? Try it and see.
112. When a steadily flowing gas flows from a larger-diameter pipe to a smaller-diameter pipe, what happens to (a) its speed, (b) its pressure, and (c) the spacing between its streamlines?
113. What physics principle underlies the following three observations? When passing an oncoming truck on the highway, your car tends to sway toward the truck. The canvas roof of a convertible automobile bulges upward when the car is traveling at high speeds. The windows of older passenger trains sometimes break when a high-speed train passes by on the next track.
114. How does an airplane adjust its angle of attack so that it is able to fly upside down?

DISCUSSION QUESTIONS (EVALUATION)

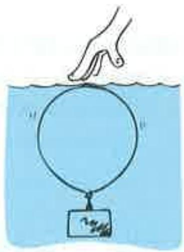
115. The photo shows physics teacher Marshall Ellenstein walking barefoot on broken glass bottles in his class. What physics concept is Marshall demonstrating, and why is he careful to ensure that the broken pieces are small and numerous? (The Band-Aids on his feet are for humor!)



116. Why is blood pressure measured in the upper arm, at the elevation of your heart?
117. Which teapot holds more liquid?



118. Suppose you wish to lay a level foundation for a home on hilly and bushy terrain. How can you use a garden hose filled with water to determine equal elevations for distant points?
119. If liquid pressure were the same at all depths, would there be a buoyant force on an object submerged in the liquid? Discuss your explanation with your friends.
120. Compared to an empty ship, would a ship loaded with a cargo of Styrofoam sink deeper or less deeply into water? Discuss and defend your answer.
121. A barge filled with scrap iron is in a canal lock. If the iron is thrown overboard, does the water level at the side of the lock rise, fall, or remain unchanged? Discuss your explanation with your discussion group.
122. A discussion of the following question raises some eyebrows: Why is the buoyant force on a submerged submarine appreciably greater than the buoyant force on it while it is floating?
123. A balloon is weighted so that it is barely able to float in water. If it is pushed beneath the surface, does it rise back to the surface, stay at the depth to which it is pushed, or sink? Discuss your explanation. (Hint: Does the balloon's density change?)



124. Greta Novak is treated to remarkable flotation in the very-salty Dead Sea. How does buoyant force on her compare when she is floating in fresh water? In answering this question, discuss differences between the volumes of water displaced in the two cases.

125. When an ice cube in a glass of water melts, does the water level in the glass rise, fall, or remain unchanged? Does your answer change if the ice cube contains many air bubbles? Discuss whether or not your answer changes if the ice cube contains many grains of heavy sand.
126. Count the tires on a large tractor-trailer that is unloading food at your local supermarket, and you may be surprised to count 18 tires. Why so many tires? (Hint: See Activity 35.)
127. Two teams of eight horses each were unable to pull the Magdeburg hemispheres apart (Figure 5.20). Why? Suppose two teams of nine horses each *could* pull them